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**NOMINAL WAGE INERTIA
IN GENERAL EQUILIBRIUM MODELS**

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Nominal Wage Inertia in General Equilibrium Models[*]

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Abstract

This paper argues that nominal wage inertia is a structural feature in low-inflation economies. Using a quarterly data set for six G7 countries we show that, unlike price inflation, nominal wage inflation responds sluggishly to both monetary and technology shocks. Accounting for this inertial behavior of nominal wages is a necessary condition for a model to capture the business cycle properties of nominal variables. We present several variants of the Calvo wage model that are able to mimic those properties in a general equilibrium frame-

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work. In contrast, models that focus on real wage rigidities or sticky prices fail to match the data.

1 Introduction

The quest for the set of frictions that, embedded in a general equilibrium framework, explains the dynamics of real and nominal variables in the business cycle has always been at central stage in macroeconomics. Until recently the prototypical sticky price model was considered the definite benchmark to study business cycles and the conduct of monetary analysis (see Woodford, 2003). However, following the seminal work of Chari, Kehoe and McGrattan (2000), several contributions have argued that a simple sticky price model does not replicate many features of the data. In parallel, other authors showed that, on average, prices behave much more flexibly than usually calibrated or estimated in those models (see Bils and Klenow, 2002). This led to a recent refocus of the literature on labor market frictions as the possible missing link needed to explain some business cycle properties of the data.

Two major recent contributions are bound to inspire and set the pace for future research in this area. The first is Christiano, Eichenbaum and Evans (2004). The impressive ability of their general equilibrium model to match the impulse responses after a monetary policy shock makes it a definite benchmark for future models to come, and has already been mimicked in

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important contributions such as Smets and Wouters (2003). A crucial feature of their model is the presence of staggered nominal wage contracts. They show that this labor market friction is crucial for the model to fit the data, unlike the sticky-price friction. This conclusion confirms the results of Huang and Liu (2002), who show that staggered wages can potentially generate more persistence in real variables than staggered prices.

The second major result appears in Chari, Kehoe and McGrattan (2002). These authors assess the fraction of business cycle fluctuations in several countries driven by efficiency wedges, labor wedges and investment wedges. They conclude that the great depressions of the US, Germany and Canada and the 1982 US recession can be accounted for with fluctuations in efficiency and labor wedges. The need to develop models with labor market frictions is a direct implication of this work. This is also in line with Bordo, Erceg and Evans (2000), who show that sticky nominal wages are crucial to understand the US Great Depression.

Building on the above literature, the contribution of this paper is twofold. First, we analyze labor market data in six G7 economies to uncover some features that may be useful in the design of frictions to incorporate in general equilibrium models. We focus on the response of inflation and of real and nominal wages to monetary and technology shocks. Second, we assess some labor market frictions that are currently embedded in macro models, in light of the labor market evidence uncovered in the previous step of the analysis. In this process, we present a novel extension of the usual baseline Calvo wage model. In this extension, a fraction of the reoptimizing households updates wages taking into account the preceding wage renegotiations.

Our key findings are as follows. First, the data clearly point to the existence of nominal wage rigidities in the countries under study. This is particularly clear when we identify the response of real and nominal wages to a technology shock. The contemporaneous fall in inflation after this shock translates into a rise in real wages, while nominal wages stay broadly unchanged. This result runs counter to the usual claim in the literature that real wages are relatively rigid. We show that this real wage rigidity is not structural. In fact, when prices change abruptly, real wages also change almost one for one (in the opposite direction). Similarly, when prices respond sluggishly to some shock, real wages also behave sluggishly. This latter case is clearly illustrated by the response of these variables to monetary policy shocks.

Second, the significant degree of inertia in the response of nominal wage inflation to both monetary and technology shocks suggests that this is a structural feature of actual economies. In order to replicate the nominal wage inertia and the real wage flexibility after a technology shock, it is necessary to account for sources of nominal rigidity in the labor market. A straightforward method to generate nominal wage inertia in a general equilibrium framework is to incorporate nominal wage contracts in the set-up. We show that, in this context, several frictions may yield analogous reduced form representations of the wage dynamics. Therefore, from a strictly positive perspective, several labor market frictions perform equally well in terms of the predictions of the respective models.

Third, we conclude that models that only incorporate price stickiness in the goods market or that focus uniquely on real wage rigidities fail to

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account for the empirical features estimated for the technology shocks in the six economies under study. The reason for this failure lies in the inability to endogenously generate the nominal wage inertia observed in the data.

The remainder of this paper is organized as follows. In section 2 we document several features of the labor market in six G7 economies, in particular the response to monetary and technology shocks. Section 3 motivates and embeds several labor market frictions in a standard general equilibrium model. Section 4 describes and evaluates the responses of several competing models to technology shocks. Concluding comments are presented in section 5.

2   Labor market features in six G7 countries

This section aims to uncover several features of the labor market that may be useful to discriminate among the frictions to incorporate in general equilibrium models. To this end we analyze the response of several macroeconomic variables to monetary and technology shocks in the US, Canada, France, UK, Italy and Germany, with a special focus on labor market variables.

This section is based on a quarterly dataset constructed for the 6 countries, which is described in Appendix A. Due to data constraints, the sample period varies between countries.

2.1   Monetary policy shocks

The monetary policy shocks are identified as the disturbance in the following interest rate reaction function (this follows Christiano, Eichenbaum and

Evans, 1997):

$$R_t = f(\Phi_t) + \varepsilon_t \qquad (1)$$

where R_t is the intervention rate of the central bank (or a short-term interest rate) and Φ_t is the information set available to the central bank when interest rate decisions are taken. The disturbance ε_t will be our measure of the monetary shock. To identify ε_t we assume that it is orthogonal to the elements in Φ_t. This corresponds to a specific timing assumption imposed in the VAR system: while the time t variables included in Φ_t affect R_t contemporaneously, these variables are not contemporaneously affected by the shock ε_t.

We estimate VARs for the six countries in our sample. All VARs are composed of four variables: real GDP, the inflation rate (measured by the change in the GDP deflator), nominal wage inflation (measured by the change in per-capita nominal wages) and the short-run nominal interest rate. We assume that the time t elements of all variables are included in Φ_t[1]. This implies that the monetary authority takes the contemporaneous information of all variables into account when taking decisions but those decisions do not affect contemporaneously any other variable in the system.

All VARs were estimated with four lags. All variables are in levels. The sample period varied from country to country due to data constraints and to the exclusion of post-1998 data for euro area countries: 1959Q1-2002Q4 for the US; 1961Q1-2002Q4 for Canada; 1978Q1-1998Q4 for France; 1962Q2-2002Q4 for the United Kingdom; 1970Q1-1998Q4 for Italy; and 1970Q1-1995Q4 for Germany. The solid lines in figure 1 represent the impulse re-

sponses of real GDP, price inflation, nominal wage inflation and the interest rate to a positive innovation in the short-run nominal interest rate in each country. The gray areas correspond to two standard error bands around the impulse responses[2].

After the contractionary monetary policy shock, the responses in the six countries show some interesting patterns. First, there is a hump-shaped response of real GDP, with the peak effect occurring after about 2 years. Second, inflation initially rises in four of the countries (and stays flat in the remaining). Overall, it is difficult to discern the evolution of inflation after the shock, except for the fact that the response is quite protracted and quantitatively small in all cases. Third, in all countries except Italy, nominal wage inflation stays flat after the shock. Combining the nominal wage and price inflation responses, we can conclude that a contractionary monetary policy shock leads to a a non-significant response in real wages in all countries[3].

All these results are consistent with the evidence presented in Christiano et al. (2004) and Edge, Laubach and Williams (2003) for the US, using VARs with a much larger set of variables. This increases our confidence in the results obtained for the broader set of countries.

Looking at this evidence, many researchers have tended to conclude that real wages are rigid. This idea has recently been restated in Danthine and Kurmann (2004), who model the process for real wages as displaying a high degree of sluggishness. We argue that this conclusion stems from the focus of the literature either on evidence from aggregate data or from impulse responses to monetary policy shocks. In fact, a very different picture emerges

once we look at the response of labor market variables to technology shocks. In this case, as will be shown in the next subsection, the response of real wages is contemporaneous and sizeable.

2.2 Technology shocks

The identification of the technology shock is analogous to Galí (1999) and Altig, Christiano, Eichenbaum and Linde (2002). Technology shocks are defined as the only source of the unit root in labor productivity[4]. The VARs are composed of the change in labor productivity, the inflation rate and the change in real wages[5].

All the VARs were estimated with four lags. The sample period varied from country to country, as follows: 1959Q1-2002Q4 for the US; 1961Q1-2002Q4 for Canada; 1978Q1-2002Q4 for France; 1962Q2-2002Q4 for the United Kingdom; 1970Q1-2000Q4 for Italy; and 1970Q1-1995Q4 for Germany. Figure 2 presents the response of the system to a positive technology shock. As in the monetary shock case, several conclusions are broadly consistent across countries.

First, in all cases the response of inflation to a technology shock is mostly contemporaneous and the largest response typically occurs on impact. This flexible response of inflation after a technology shock is a robust pattern in this set of countries (see Alves, 2004). Sticky prices are therefore not a structural friction in actual economies. Second, the response of the change in real wages is highly significant on impact, and mirrors the contemporaneous response of inflation (with the exception of France). Third, the response of

nominal wage inflation to the technology shock is contemporaneously non-significant in all cases. In the quarters after the shock, nominal wage inflation falls in a hump-shaped pattern (with the exception of Germany, where it is always non-significant). We therefore conclude that after a technology shock price inflation does not display any inertial behavior. In contrast, nominal wage inflation reacts sluggishly, in line with the observed response to monetary policy shocks.

Again, these results are perfectly consistent with the evidence from larger VARs for the US, as in Christiano et al. (2004) and Edge et al. (2003). The flexibility of real wages in response to technology shocks can also be found in Francis and Ramey (2002). These results clearly suggest that a structural rigidity in the labor market lies not in the real wage decision but in the nominal wage decision.

Recently there has been a growing interest in the behavior of employment after a technology shock (see Altig et al., 2002). To analyze this issue, we also estimated VARs with the change in the employment rate added to the original system. The results for this variable are presented in the fourth column of figure 2. We conclude that the employment rate falls after a positive technology shock in all countries except Germany. This conclusion is consistent with the results presented in Galí (1999), who also estimates the VAR with the employment rate in first differences. Altig et al. (2002) argue that the conclusions on this issue are sensitive to the variables included in the VAR and to the degree of differencing of the data. This paper does not attempt to contribute thoroughly to this ongoing discussion, but suggests that a cross-country analysis may enrich the debate and bring forth more

consistent insights. For example, the issue of overdifferencing the data does not apply to the European data since - for the available sample periods - the employment rate is clearly a non-stationary variable in all European countries[6].

3   Embedding nominal wage stickiness in a general equilibrium model

The evidence discussed in section 2 forcefully suggests that the main underlying friction in the labor market cannot be an exogenously-given constraint on the price and/or real wage adjustment by households and firms. In fact, the evidence shows that real wages are quite flexible in response to technology shocks, albeit being quite flat in response to monetary policy shocks. In contrast, the response of nominal wages to both the monetary and technology shocks displays a significant degree of inertia. This suggests that only nominal wage stickiness may apply as a structural friction in the labor market.

In this section we embed, in turn, three types of nominal wage stickiness in an otherwise standard general equilibrium model, which builds closely on Christiano et al. (2004). The three labor market frictions correspond to the standard Calvo wage model and two related variants of the model. In section 4 we compare the predictions of these models after a technology shock with those of a standard sticky-price model and a standard fair-wage model.

The rationale for the Calvo wage model is rooted on the explicit or implicit

long-term wage agreements that are prevalent in all industrialized countries with low or moderate levels of inflation[7]. Despite the heterogeneity in contract length, a one-year minimum threshold seems to hold in many countries and for many historical periods[8]. Further, this pattern is not exclusive of formal labor contracts. Workers not covered by terms of a collective bargaining agreement also adjust wages at rather long discrete intervals, and usually with at least one year intervals (see Taylor, 1999).

This evidence suggests that the discrete renegotiation of wages can be proxied by an exogenous constraint facing households and firms. However, it should be stressed that for a model with nominal wage contracts to be used sensibly as a laboratory of the economy, it is necessary that the experiments we are subjecting our model to do not trigger significant changes in contract duration. For example, if our aim is to analyze significant (dis)inflationary experiments, assuming a constant contractual structure would obviously be wrong.

The remainder of this subsection characterizes the behavior of the agents in the general equilibrium model. Subsection 3.1 describes the households' decisions, with the exception of the wage decision. In subsection 3.2 we present the three competing modeling strategies that take into account the presence of nominal wage frictions in the households' wage decision. Subsections 3.3 to 3.5 describe the behavior of firms, the financial intermediaries and the monetary authority.

3.1 Households

There is a continuum of households, indexed by $j \in [0, 1]$. In the beginning of each period, all the money in the economy is held by the households. During the period the jth household makes several decisions in order to maximize utility.

First, the household decides the level of consumption. It is assumed that there are internal habits in consumption preferences. Second, the household supplies a differentiated type of labor. Households sell their labor to a representative firm that transforms the individual differentiated labor supplies into a homogeneous composite input. This composite is then demanded by all firms in the economy. Only a fixed fraction of households is able to reoptimize wages in each period.

Third, since the wage rate (and labor supply) differs between households, there is a potential for heterogeneity in their allocations. To sidestep this issue, we follow most of the literature and assume that there are state-contingent securities that ensure that in equilibrium households choose the same level of consumption and asset holdings (see Erceg, Henderson and Levin, 2000 and Christiano et al., 2004). Fourth, the household chooses the level of cash-balances (which yield utility directly) and the level of deposits with the financial intermediaries to hold in each period.

Technology shocks, which are assumed to be the only source of uncertainty in the model, occur in the beginning of the period. Households make all their decisions after observing these shocks. At the end of the period, the households receive the dividends from the firms, the dividends plus the

deposits (with interest) from the financial intermediaries and the return from the state-contingent securities.

The households maximize utility subject to an asset evolution equation. The problem of the representative household j is the following (where the notation reflects the fact that households are only heterogeneous with respect to wages and labor supply)

$$\max \quad E_t^j \sum_{t=0}^{\infty} \beta^t \left[u^j \left(C_t, H_t, 1 - N_t^j \right) + v \left(\frac{Q_t}{P_t} \right) \right]$$

$$st \quad M_{t+1} = Q_t + W_t^j N_t^j + R_t \left(M_t - Q_t \right) - P_t C_t + D_t + Z_t^j \quad (2)$$

where C_t is time t consumption, H_t is the habit stock, which is equal to bC_{t-1}, $\left(1 - N_t^j \right)$ is household j's leisure, $\frac{Q_t}{P_t}$ are real cash balances, M_t is the household's stock of money held at the beginning of time t, W_t^j is the nominal wage rate, N_t^j is the labor supply, $(M_t - Q_t)$ are deposits with the financial intermediaries, D_t are dividends from the firms, and Z_t^j is the net cash flow arising from the participation in the state-contingent market in period t.

Consumption C_t is a composite good (with differentiated goods indexed by a), defined as

$$C_t = \left[\int_0^1 c_t(a)^{\frac{\epsilon-1}{\epsilon}} da \right]^{\frac{\epsilon}{\epsilon-1}} \quad (3)$$

where $\epsilon > 1$ is the elasticity of substitution between any two goods.

The aggregate price level P_t is defined as

$$P_t = \left[\int_0^1 P_t(a)^{1-\epsilon} da \right]^{\frac{1}{1-\epsilon}} \quad (4)$$

where $P_t(a)$ is the price of each type of good a in units of money.

We assume that preferences are separable in consumption and leisure, and have the following functional form:

$$u^j \left(C_t, H_t, 1 - N_t^j \right) = \frac{1}{1-\sigma} (C_t - H_t)^{1-\sigma} - \frac{\left(N_t^j \right)^{1+\chi}}{1+\chi} \tag{5}$$

In each period, the household decides how much funds to hold as cash-balances and how much to apply as deposits with the financial intermediaries.

Combining the first order conditions relative to consumption and the money stock we can derive the intertemporal condition

$$\frac{u_C(t)}{P_t} = \beta E_t \left[R_{t+1} \frac{u_C(t+1)}{P_{t+1}} \right] \tag{6}$$

The first-order condition of the households' problem (2) relative to Q_t is (we denote $q_t = \frac{Q_t}{P_t}$)

$$\frac{v_q(t)}{P_t} + \lambda_t(1 - R_t) = 0 \tag{7}$$

where λ_t is the Lagrange multiplier on the asset evolution equation. From the first order condition with respect to consumption and (7) we obtain the relation between $u_C(t)$ and $v_q(t)$:

$$v_q(t) = u_C(t)(R_t - 1) \tag{8}$$

Equation (8) simply states that the marginal utility from holding cash balances $v_q(t)$ must equal the marginal utility from holding deposits $u_C(t)(R_t - 1)$.

3.2 The wage decision

In this subsection we present the households' wage decision. We start by describing the main building blocks of the base Calvo wage model (subsubsection 3.2.1) and then turn to two variants of that model that yield inertia in the nominal wage inflation process (subsubsections 3.2.2 and 3.2.3).

3.2.1 The base Calvo wage model

In presenting the main features of the base Calvo wage model, we follow the seminal contribution of Erceg et al. (2000). As mentioned above, the households are monopolistic suppliers of their own differentiated labor N_t^j. Households sell their labor to a representative and competitive firm (the aggregator) that transforms the individual differentiated labor supplies into an homogeneous composite input, N_t. All firms in the economy hire this composite labor input (and by the same amount).

The production function of the aggregator is

$$N_t = \left[\int_0^1 \left(N_t^j \right)^{\frac{1}{\lambda_w}} dj \right]^{\lambda_w} \tag{9}$$

The problem of the aggregator is to minimize the cost of producing a given amount of N_t taking W_t^j as given. The first order condition to this problem yields

$$N_t^j = \left[\frac{W_t^j}{W_t} \right]^{\frac{\lambda_w}{1-\lambda_w}} N_t \tag{10}$$

which represents the demand for each household's differentiated type of labor. The elasticity of substitution among the different types of labor is given by

$\frac{\lambda_w}{\lambda_w-1}$.

The aggregate wage rate equals

$$W_t = \left[\int\limits_0^1 \left(W_t^j\right)^{\frac{1}{1-\lambda_w}} dj\right]^{1-\lambda_w} \tag{11}$$

In each period only a fraction of the households $(1 - \xi_w)$ is able to change nominal wages optimally. This probability is independent of the individual history of each household[9]. In the base Calvo model, the fraction ξ_w that is unable to reoptimize wages keeps nominal wages constant. This nominal wage friction captures in a precise sense the existence of fixed nominal wages in the economy.

Households weight the loss and gain in utility from a change in the nominal wage, given the demand for labor (10) and their budget constraint. The first order conditions of the household yield

$$E_t \sum_{i=0}^{\infty}(\xi_w\beta)^i \widetilde{N}_{t+i}^j \left[\frac{\widetilde{W}_t}{P_{t+i}}\frac{u_{C,t+i}}{\lambda_w} - \left(\widetilde{N}_{t+i}^j\right)^\chi\right] = 0 \tag{12}$$

where $\widetilde{W}_t$ and $\widetilde{N}_{t+i}$ are the nominal wage and amount of labor chosen by the household in periods t and $t+i$ respectively (the latter given the wage chosen at t)[10].

The aggregate nominal wage level is given by:

$$W_t = \left[(1 - \xi_w)\widetilde{W}_t^{\frac{1}{1-\lambda_w}} + \xi_w\left(W_{t-1}\right)^{\frac{1}{1-\lambda_w}}\right]^{1-\lambda_w} \tag{13}$$

Log-linearizing the first-order condition (12) around a zero-inflation steady

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state[11], imposing the labor demand equation and using (13) yields the following wage adjustment equation:

$$\widehat{w}_t = \frac{\beta}{1+\beta} E_t \widehat{w}_{t+1} + \frac{\beta}{1+\beta} E_t \widehat{\pi}_{t+1}$$
$$+\frac{1}{1+\beta} \widehat{w}_{t-1} - \frac{1}{1+\beta} \widehat{\pi}_t + \kappa \cdot \left[-\widehat{u}_{C,t} + \chi \widehat{N}_t - \widehat{w}_t \right] \qquad (14)$$

where $\kappa = \frac{(\lambda_w - 1)}{\chi \lambda_w + \lambda_w - 1} \frac{(1-\xi_w)(1-\xi_w \beta)}{\xi_w (1+\beta)}$, w_t is the real wage, π_t is the rate of inflation at time t and hats represent percent deviations from the steady state. In the base Calvo framework, the real wage is thus a function of lagged and expected real wages, of current and expected inflation, and of the usual determinants of the labor/leisure decision.

One of the features of the Calvo wage setting curve is that the households are not on their labor supply curves every period. This is due to the nominal wage constraint. More interestingly, the aggregate wage dynamics becomes almost independent from the households' preferences, even for moderate degrees of contract length. In fact, for the values usually estimated or calibrated in the literature, the size of κ - the coefficient multiplying the standard intratemporal determinants of wages in equation (14) - is minimal. For example, in Smets and Wouters (2003) the parameters ξ_w and λ_w are, respectively, 0.74 and 1.29 for the euro area. In Christiano et al. (2004) the parameters ξ_w and λ_w are, respectively, 0.64 and 1.05 for the US. For these combinations of parameters, and with $\beta = 0.99$ and $\chi = 1$, the value of the coefficient multiplying the wages' intratemporal determinants is always around 0.005. It can thus be concluded that the presence of nominal wage contracts underweights considerably the relevance of the households' in-

tratemporal marginal rate of substitution between consumption and leisure in the aggregate wage dynamics.

This feature of the model is traceable to two main factors: on the one hand, the elasticity of substitution between labor types; on the other, the wage contract duration. Concerning the latter, it is straightforward to note that the higher the contract duration, the smaller the weight of each periods' intratemporal fundamentals to the wage decision. As for the first, it is important to note that the higher the elasticity of substitution between labor types (i.e., the lower is λ_w), the higher will be the labor response to a given change in relative wages. This relation is clear from equation (10), which governs the labor demand faced by each household. When a shock hits the economy, the households who are able to choose wages optimally know that the labor demand targeted at their labor services is affected by any relative wage change. Since households have a desire to smooth labor supply over time (governed by parameter χ), they will choose not to change wages by much even when their frictionless intratemporal determinants change. This explains why the marginal rate of substitution between consumption and leisure weights modestly in the aggregate wage dynamics in a Calvo wage model.

It is also interesting to analyze the equation for the change in nominal wages. After simple manipulations, equation (14) can be rewritten as

$$\Delta \widehat{W}_t = \beta E_t \Delta \widehat{W}_{t+1} + \kappa \left(1 + \beta \right) \cdot \left[-\widehat{u}_{C,t} + \chi \widehat{N}_t - \widehat{w}_t \right] \qquad (15)$$

Equation (15) resembles a new-Keynesian Phillips curve, as applied to

nominal wages instead of prices. In this model nominal wage inflation is a purely forward-looking variable. In fact (15) implies that nominal wage inflation equals a discounted stream of current and expected future gaps between the real wage and the households' average marginal rate of substitution between consumption and leisure. Thus, any inertia in nominal wages must arise from an inertial evolution of the intratemporal determinants of real wages. In the next subsubsections we will analyze two extensions of the Calvo wage model which embody intrinsic nominal wage inflation inertia.

3.2.2 The backward Calvo wage model

The first extension of the Calvo model is presented in Christiano et al. (2004), and will be henceforth denoted "backward Calvo". The backward Calvo model assumes that households who are not able to optimally adjust their wages do not keep their wages fixed. Instead, they follow a rule of thumb updating their wage with the previous period's rate of inflation.

The backward Calvo model yields different dynamics in comparison to the base Calvo model. In particular, nominal wage inflation in this case evolves according to the following equation:

$$\Delta \widehat{W}_t = \beta E_t \Delta \widehat{W}_{t+1} - \beta \widehat{\pi}_t + \widehat{\pi}_{t-1} + \kappa \left(1 + \beta\right) \cdot \left[-\widehat{u}_{C,t} + \chi \widehat{N}_t - \widehat{w}_t\right] \qquad (16)$$

Two features are worth emphasizing in this equation. First, there is an accelerationist term between previous and current inflation, which is absent in the base Calvo model. Second, past inflation influences the wage inflation dynamics, which improves the ability of this model to match the nominal

inertia that characterizes the data. However, note that this is achieved by modeling contracts that are indexed on a quarterly basis to previous period's inflation. It is clear that this contracting scheme is not dominant in developed economies[12]. Taking seriously into account the empirics of wage renegotiations, one would attribute a very small weight to these quarterly wage indexation practices. The model would thus collapse into the base Calvo model.

3.2.3   The hybrid Calvo wage model

In the second extension of the base model, that we call "hybrid Calvo", we retain the fact that households have their nominal wages fixed for a number of periods. The difference with respect to the base Calvo model lies in the behavior of the agents who are able to change wages in each period. In particular, we assume that a fraction $(1-\phi)$ of those agents behaves optimally and a fraction ϕ merely sets the nominal wage equal to the previous average reset wage plus inflation[13].

Where do these non-optimal wage setters come from? They can be rationalized by observing that, in many labor markets, a fraction of firms follows the wage increase set in specific "leading" sectors of the economy, such as the public sector or important industrial firms or groups of firms. This type of behavior may imply $\phi > 0$.

Aggregate nominal wage level in this set-up is given by:

$$W_t = \left[(1-\xi_w)\widetilde{W}_t^{*\frac{1}{1-\lambda_w}} + \xi_w \left(W_{t-1}\right)^{\frac{1}{1-\lambda_w}} \right]^{1-\lambda_w} \tag{17}$$

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where $\widetilde{W}_t^*$ is the average re-set wage in period t. This re-set wage is calculated as a weighted average of the fraction $(1-\phi)$ of households who set the wage as in the standard Calvo framework and the fraction ϕ that update the previous period's average reset wage with lagged inflation.

The nominal wage growth in this case is described by the following equation[14]:

$$
\begin{aligned}
\Delta\widehat{W}_t &= \frac{\xi_w}{\phi\left(1 - \xi_w + \xi_w\xi_w\beta\right) + \xi_w}\left(\beta E_t\Delta\widehat{W}_{t+1} + \phi\Delta\widehat{W}_{t-1}\right) \\
&\quad - \frac{\phi(1 - \xi_w)}{\phi\left(1 - \xi_w + \xi_w\xi_w\beta\right) + \xi_w}\left(\beta\xi_w\widehat{\pi}_t - \widehat{\pi}_{t-1}\right) \\
&\quad + \kappa\frac{(1 - \phi)\,\xi_w\,(1 + \beta)}{\phi\left(1 - \xi_w + \xi_w\xi_w\beta\right) + \xi_w}\left[-\widehat{u}_{C,t} + \chi\widehat{N}_t - \widehat{w}_t\right] \qquad (18)
\end{aligned}
$$

In this framework nominal wage inflation depends not only on future expected nominal wage growth and inflation but also on past nominal wage growth and inflation. Therefore this model incorporates intrinsic wage inflation inertia, without having to resort to nominal wage indexation as in the "backward Calvo" case.

Naturally, the added flexibility arising from the possibility that $\phi > 1$ may help to fit this Calvo wage curve to the data. However, the relevance of this extension can only be assessed by analyzing actual wage bargaining practices across firms and sectors in different countries. Merely relying on empirical estimations of the reduced form equations may be misleading in this respect. More microeconomic studies are therefore needed in order to characterize the structural fundamentals of the wage bargaining relation.

3.3 Firms

Firms have access to a labor-only production technology

$$y_t(a) = z_t \left(N_t\right)^{1-\alpha} \tag{19}$$

where z_t is an aggregate technology shock. The firms hire the composite labor at the aggregate wage rate W_t and need to borrow their wage bill from the financial intermediaries at a rate of interest R_t.

The demand for firm a's output is given by the households' problem (2) (where we also used the clearing condition that consumption of each good equals output):

$$y_t(a) = \left[\frac{P_t(a)}{P_t}\right]^{-\epsilon} Y_t \tag{20}$$

The firms choose the price to maximize profits. Since there is complete symmetry across firms, they all choose the same price. Taking into account that the demand elasticity facing the firms' products is ϵ, the first-order condition of this problem implies that prices are set as a constant mark-up over marginal costs:

$$P_t = P_t(a) = \frac{\epsilon}{\epsilon - 1} R_t W_t \frac{1}{1 - \alpha} \frac{1}{z_t} \left(N_t\right)^{\alpha} \tag{21}$$

3.4 Monetary authority

Since we will focus the analysis on the impact of aggregate technology shocks in the economy, we have to describe the behavior of the monetary authority in response to these shocks. We assume that the monetary authority follows

a simple backward-looking Taylor rule, of the form

$$\widehat{R}_t = \omega_0 \widehat{R}_{t-1} + \omega_1 \widehat{\pi}_{t-1} \tag{22}$$

where the parameter ω_0 captures the degree of interest rate smoothing and ω_1 measures the response of the interest rate to deviations of lagged inflation from the zero inflation steady state level. In subsection (4.3) we will assess the sensitivity of the results to alternative interest rate rules.

3.5 Financial intermediaries

There is complete integration of the financial markets. The financial intermediaries channel the supply of loans to the respective demand. The supply of loans corresponds to the deposits of the households with the financial intermediaries $(M_t - Q_t)$. The demand for loans comes from the firms and equals the wage bill $(W_t N_t)$.

3.6 Clearing conditions

In equilibrium, all markets clear. The loan market clearing condition is:

$$W_t N_t = M_t - Q_t \tag{23}$$

The clearing of the goods market implies that consumption of each good a equals output:

$$c_t(a) = y_t(a) \tag{24}$$

The linearized resource constraint can be written, to a first-order approximation, as follows[15]:

$$\widehat{C}_t = \widehat{z}_t + (1 - \alpha)\,\widehat{N}_t \tag{25}$$

4 Model responses to technology shocks

In this section we present the responses of several labor market models to a technology shock. We will conclude that, from a positive perspective, it is difficult to discriminate between some of the Calvo-wage variants. We will also argue that standard models with nominal price stickiness or real wage rigidities are at odds with the data.

We start by presenting the parameterization of the various models (subsection 4.1). We then analyze the responses of the models to a technology shock (subsection 4.2), with a special emphasis on the response of price inflation, nominal wage inflation and real wage changes. Finally, subsection 4.3 undertakes several sensitivity exercises concerning the parameterization of the models. In particular, we will assess the sensitivity of the results to the assumed degree of nominal wage rigidity and to the interest rate rule followed by the monetary authority.

4.1 Parameterization

Table 1 presents the baseline calibration used in the simulations below. Most of the values are common in the literature, and close for example to the parameters estimated and calibrated in Christiano et al. (2004) or Smets and Wouters (2003). Several features of this calibration can be highlighted.

The value of β corresponds to a steady state annualized real interest rate of 3 per cent. This value is consistent to the average real interest rate found in the six countries under study in the post-war period. The value of the habit persistence parameter b is comparable to the estimates of Christiano et al. (2004) for the US and Smets and Wouters (2003) for the euro area. The parameter χ, which determines the Frisch intertemporal labor supply elasticity, is between $\chi = 1$ assumed by Christiano et al. (2004) and $\chi = 1.7$ estimated by Smets and Wouters (2003). We calibrate the average wage duration to equal one year, which is consistent with the evidence reported in section 3.1. The parameters related to the households' portfolio decisions (γ and ψ) are compatible with those estimated in Christiano et al. (2004).

The firms' average mark-up is calibrated as $\theta = 1.2$. This is also the value estimated by Christiano et al. (2004) and Smets and Wouters (2003). As for the wage mark-up, we assume $\lambda_w = 1.10$, which is between the assumption in Christiano et al. (2004) of $\lambda_w = 1.05$ and the estimate in Smets and Wouters (2003) of $\lambda_w = 1.29$.

The parameters governing the response of the interest rate to a technology shock are close to those reported in Smets and Wouters (2003) for the euro area and Orphanides (2003) for the US. Finally, we assume that the fraction of backward-looking wage setters in the hybrid Calvo wage model is 0.5. The sensitivity of the results to this parameter is assessed in subsection 4.3.

4.2 Responses to technology shocks

Figure 3 compares the impulse responses to a positive and persistent ($\rho_z = 0.99$) technology shock in the base Calvo, the backward Calvo and the hybrid Calvo models. The figure presents the response of price inflation, nominal wage inflation, the change in real wages, employment, consumption (which equals output) and the interest rate.

Several conclusions can be drawn from the figure. First, all the models are able to simultaneously capture the sharp fall in inflation and the mirrored rise in real wages in the period of the shock. The models also capture quite accurately the nominal wage inertia after a technology shock.

Second, figure 3 reveals that it is difficult to distinguish between the backward and the hybrid Calvo models from a strictly positive point of view. In fact, both models seem to perform empirically well, both from a qualitative and a quantitative point of view[16]. The differences between the models' impulse responses are actually smaller than the confidence intervals usually estimated in the VAR literature. This can be confirmed by comparing the models' responses with the estimated impulse responses presented in section 2. Other criteria besides the models' predictions seem therefore needed to discriminate between these models. We discuss some of these criteria in the conclusion.

Even though the above models are consistent with the evidence presented in section 2, there are other models that fail to capture the distinct responses of price inflation and wage inflation to a technology shock. In this sense, this shock is an important laboratory to discriminate between several competing

frictions in a general equilibrium framework. To assess this assertion, we now compare the performance of the backward Calvo wage model with a standard sticky-price model and the fair-wage model presented in Danthine and Kurmann (2004).

The sticky price model corresponds to the model described in section 3 but without any nominal wage rigidities and with firms setting prices à la Calvo. In this case, equation (21) is replaced by the following standard Calvo Phillips curve:

$$\widehat{\pi}_t = \frac{\beta}{1+\beta}E_t\widehat{\pi}_{t+1} + \frac{1}{1+\beta}\widehat{\pi}_{t-1} + \frac{\left(1-\xi_p\right)\left(1-\xi_p\beta\right)}{\xi_p(1+\beta)}\left(\widehat{w}_t + \widehat{R}_t + \alpha\widehat{N}_t\right) \quad (26)$$

Note that we assume that the fraction of firms that does not reoptimize prices in each quarter updates prices with lagged inflation, as in Christiano et al. (2004). We calibrate this fraction to equal 0.75, which corresponds to an average period of one year between consecutive price reoptimizations.

As for the fair-wage model, we follow the recent contributions of Collard and de la Croix (2000) and Danthine and Kurmann (2004). In their models, the firms' production function embodies the work-effort supplied by households. It is assumed that this effort is a positive function of current and lagged real wages and of the aggregate level of unemployment. In equilibrium, it can be shown[17] that firms choose to guarantee a constant level of work effort (as in Solow, 1979). In this case, real wages evolve as follows:

$$\widehat{w}_t = \widehat{w}_{t-1} + \zeta\widehat{N}_t \quad (27)$$

We calibrate the elasticity ζ as in Danthine and Kurmann (2004), which estimate it to equal 0.035. The unitary coefficient on lagged real wages is the preferred in Collard and de la Croix (2000). Danthine and Kurmann (2004) estimate it to equal 0.991.

Figure 4 compares the responses of the backward Calvo model, the sticky price model and the fair-wage model to a technology shock. Several features are worth highlighting from the figure. First, the fair-wage model does not display any nominal wage inflation inertia after a technology shock. This is due to the high degree of real wage rigidity embodied in the model. This implies that real wages do not jump after the technology shock and that nominal wage inflation follows quite closely the path of contemporaneous price inflation. This stands in contrast with the evidence presented in section 2. The real wage rigidity also explains the model's strong propagation effects of the technology shock on employment and consumption. These propagation effects are notably highlighted in Danthine and Kurmann (2004).

Second, figure 4 also confirms that a sticky-price model without nominal wage frictions is not able to capture the nominal effects of a technology shock. In particular, this model fails to deliver the contemporaneous fall in inflation and the nominal wage inertia after a technology shock. We therefore conclude that an exogenous constraint on the price-setting behavior by firms is not the underlying friction driving the aggregate nominal inertia observed in the data.

In conclusion, the nominal effects of a technology shock constitute an important information set to discriminate between models. In order to capture both the nominal wage inertia and the flexible inflation response to that

shock, a general equilibrium model needs to incorporate sources of nominal wage stickiness. It is clear that a model with only real wage rigidities and/or nominal price rigidities will be at odds with the data. In contrast, models with nominal wage rigidities easily capture the distinct responses of price inflation and nominal wage inflation after a technology shock.

4.3   Sensitivity analysis

In this subsection we evaluate the impact of some of the parameters on the results of the models. The focus here will be on the Calvo wage models. Figure 5 presents three sensitivity exercises. In the first two columns we assess the sensitivity of the base and backward Calvo wage models to the degree of nominal wage rigidity (with expected contract duration varying from 2 to 8 quarters). The third exercise assesses the sensitivity of the hybrid Calvo model to the fraction of backward-looking optimizing agents. The main idea stemming from figure 5 is that the nominal response of the three models to a technology shock is not affected to a significant degree in any of the cases under study. However, the response of real variables is amplified with the degree of nominal rigidity, in particular in the backward and hybrid Calvo models.

In figure 6 we report the sensitivity of the results to different interest rate rules. All the rules share the same degree of interest rate smoothing ($\omega_0 = 0.8$) and the same coefficient on the inflation rate ($\omega_1 = 0.5$). The difference between the rules lies in the rate of inflation that the monetary authority incorporates in the rule: in the backward rule, it is lagged inflation;

in the contemporaneous rule, it is current inflation; in the forward rule, it is the one-period ahead expected inflation. Two main conclusions may be highlighted from figure 6. The first is that the equilibrium response of real and nominal variables to a technology shock is not invariant to the interest rate rule followed by the monetary authority (this is also emphasised, for example, in Galí, López-Salido and Valés, 2003). For example, figure 6 shows that the response of employment to a technology shock crucially depends not only on the underlying frictions in the nominal wage-setting process but also on the monetary policy rule in place. The second conclusion stemming from the figure is that the main qualitative features of the response of real wages and price and nominal wage inflation are preserved under all rules. The evaluation of the models - at least when based on their predictions concerning these variables - is therefore unchanged under the three rules.

The above exercises confirm the robustness of the Calvo wage models in replicating the flexibility of price inflation and the stickiness of nominal wages in response to a technology shock. As is clear from figure 6, a further discrimination between models may require a deeper understanding of the response of real variables to this shock (namely the response of employment) and a more complete knowledge of the behavior of the monetary authorities in the sample period under study.

5 Conclusion and final remarks

Labor market frictions are key to understanding the general equilibrium dynamics of economies. In this paper we showed that the behavior of nominal

wage inflation after monetary and technology shocks gives important insights concerning the frictions needed to replicate several features of the data in a general equilibrium framework.

We identified a substantial degree of inertia in the response of nominal wages to both monetary and technology shocks. This contrasts with the response of price inflation to those shocks. In fact, while price inflation responds sluggishly to monetary policy shocks, it behaves flexibly in response to technology shocks.

Models featuring only real wage rigidities or price rigidities fail to capture those patterns. This forcefully suggests that an important friction in the labor market lies in the nominal wage decision. Incorporating nominal wage frictions in general equilibrium models - or features that endogenously generate nominal wage sluggishness - is therefore key to match the empirical behavior of nominal wages.

However, there are several nominal frictions that yield analogous labor market dynamics. From a purely positive point of view, several models (and underlying frictions) are indistinguishable. This is the case, for example, of a model where wages are contracted for some quarters and are continuously indexed to past inflation and of a model where wages are set for some quarters and where a fraction of the agents who is able to reoptimize wages updates past reset wages with lagged inflation. Even though the final reduced form equations of these models are close, the insights stemming from each model are obviously different.

To evaluate the importance of each labor market friction for modeling purposes, the respective model's predictions should be just one among the

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decision criteria. Equally valuable are the correspondence of each friction with empirical labor market evidence and the possibility of rooting them in a microfounded model.

The first criterion requires that models explicitly take into account the discreteness in the timing of wage renegotiations. In fact, a lower bound of one year between wage renegotiations seems prevalent in all economies with low to moderate rates of inflation. It introduces a constraint on the wage bargaining between households and firms that may affect the equilibrium of the economy. This feature of the environment is bound to be invariant to small policy changes. For these experiments, embedding nominal wage frictions in the model is thus not only appropriate but also desirable.

Rooting the model on labor market evidence also concerns the calibration of the model. Simply allowing the parameters to vary in order to achieve the best fit of the model may be a misleading strategy, since the resulting parameter values may simply be incomprehensible. For models to be relevant laboratories in the description and rationalization of economic outcomes, it becomes crucial to anchor the calibration in as much observable features as possible. This should be at hand in the case of wage contract duration.

The second criterion simply recalls that models which explicitly model the agents' optimizing decisions are insightful for analyzing the agents' economic choices, in contrast with reduced form specifications, as in Taylor (1980), Fuhrer and Moore (1995) or the fair-wage model. Adding parameters and degrees of freedom to the models does not obviously harm their ability to fit the data. However, it undermines our ability to understand it (Lucas, 1980). This is the basis for anchoring models on solid microfoundations. Absent

these foundations it becomes difficult to rationalize and understand observed patterns of behavior.

Further study of the characteristics of the wage bargaining process is needed before any model can be presented as a truly structural description of the mechanics in the labor market. Bridging the theoretical and the empirical levels on these issues is a demanding task. Given the flexibility of several conflicting theoretical models, a further understanding of labor market practices and institutions may have to be ahead of theory in the near future.

Notes

[1]As shown in Christiano, Eichenbaum and Evans (1999), the impulse response functions to a monetary policy shock are independent of the ordering of the variables in Φ.

[2]These are Monte Carlo Bayesian confidence intervals, computed using random draws from the posterior distribution of the covariance matrix of innovations and the reduced form coefficient matrix.

[3]This was also confirmed by directly estimating a VAR with real wages instead of nominal wages.

[4]As emphasized by Altig et al. (2002), there are other shocks that may affect labor productivity in the long-run, such as changes in capital taxes. The arguments in this subsection do not rely on the precise origin of the underlying shock.

[5]In order to use the Blanchard-Quah identification scheme, all variables

must be in stationary form. Standard unit root tests easily reject the existence of a unit root for the variables in all countries (with the only exception being the inflation rate, in particular in France).

[6]If, nonetheless, we compute bivariate VARs with the change in productivity and the *level* of the employment rate for all six countries in the sample, the results are the following: in the US, Canada, Italy and Germany, the employment rate rises after a positive technology shock; in France and the UK, the employment rate falls.

[7]This was also the rationale for the early wage contracting models of Fisher (1977) and Taylor (1980).

[8]A simple survey of some studies (see, for example, Dufresne and Mermet, 2001 and Mermet, 2002) confirms this one-year representative threshold for Australia, Austria, Belgium, Bulgaria, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Latvia, Netherlands, Poland, Portugal, New Zealand, Norway, Slovakia, Slovenia, Sweden, Switzerland, Turkey, UK and US.

[9]This is completely analogous to the model in Calvo (1983) but applied to wage decisions instead of prices.

[10]All households that are able to reoptimize wages choose the same wage. Therefore, $\widetilde{W}_t$ and $\widetilde{N}_t$ need not be indexed by j.

[11]This is without loss of generality. With a steady-state inflation $\pi > 0$, equation (14) would simply include additional terms related to the steady-state inflation π.

[12]Italy was until recently an interesting exception in this respect. Since 1946, there was an agreement to index industry wages to the cost of living

every quarter. This agreement was only abandoned in 1992.

[13] This formulation is inspired in the Hybrid Phillips curve proposed by Galí and Gertler (1999).

[14] A full derivation of the hybrid wage model is presented in an appendix available upon request.

[15] The aggregate goods market clearing conditions is $C_t = \Xi_t z_t (N_t)^{1-\alpha}$, where $\Xi_t = \left(\frac{W_t^*}{W_t}\right)^{\frac{\lambda_w(1-\alpha)}{\lambda_w-1}}$, and $W_t^* = \left[\int_0^1 \left(W_t^j\right)^{\frac{\lambda_w}{1-\lambda_w}} dj\right]^{\frac{1-\lambda_w}{\lambda_w}}$. As shown in Erceg et al. (2000) and Christiano et al. (2004), Ξ_t is constant to a first-order approximation.

[16] In figures available upon request, we also conclude that the Calvo wage models are close from a positive point of view in the case of monetary policy shocks. In fact, all Calvo wage models reproduce the sluggish response of inflation and the small response of real wages after a monetary policy shock. The inertial behavior of inflation is due to the inertia in marginal costs. The differences in the nominal behavior between the models are rooted in the different labor market frictions. In fact, while the backward and hybrid Calvo models embody intrinsic nominal wage inflation inertia, the base Calvo does not. The first models are thus better able to capture the slow and gradual response of both price and wage inflation to a monetary policy shock that we observe in the data.

[17] A full derivation of the fair-wage model is available in an appendix available upon request.

A Description of the data

Data for the US

The raw series used for the US were the following: non-farm business sector gdp deflator (source: BEA); Gross Domestic Product, in chained (1996) dollars (source: BEA); Federal Funds rate (source: IMF); nominal wages per hour (source: BLS); and, employment rate (source: BLS).

Data for the UK

The raw series used for the UK were the following: implied deflator of Gross Value Added at basic prices (source: Office of National Statistics); Gross Domestic Product at constant 1995 prices (source: Office of National Statistics); overnight interbank rate, retropolated (before 1972Q1) with the Treasury Bill rate (Source: IMF); nominal wages per worker (source: Office of National Statistics); and, UK workforce jobs (source: Office of National Statistics) retropolated (before 1978Q2) with series from the UK Department of Labor.

Data for Canada

The raw series used for Canada were the following: GDP deflator (source: IMF); real output at basic prices (source: OECD Quarterly National Accounts); official discount rate (source: IMF); total compensation (source: OECD); and, civilian employment (source: OECD).

Data for Italy

The raw series used for Italy were the folowing: GDP at basic prices deflator (source: Conistat); value added at basic prices (source: Conistat); three-month money market interest rate (source: IMF); wages per person

(source: IMF); and, civilian employment (source: OECD).

Data for France

The raw series used for France were the following: non-financial enterprises producer prices (source: INSEE); Gross Domestic Product (source: INSEE); call money rate (source: IMF); nominal wages per hour (source: BLS); and, employees in market industry and services (source: OECD).

Data for Germany

The raw series used for Germany were the following: GDP deflator (source: IMF); GDP volume at 1995 prices (source: IMF); call money rate (Source: IMF); nominal hourly earnings in manufacturing (source: OECD); and, wage and salary earners (source: Bundesbank).

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β	0.9926	quarterly discount rate
b	0.7	habit preferences for consumption
σ	1.5	curvature of the preferences for consumption
χ	1	curvature of the preferences for leisure
$1-\alpha$	0.64	labor share in the economy
$\frac{\epsilon}{\epsilon-1}$	1.2	firm mark-up
λ_w	1.1	wage mark-up
γ	20	parameter from $v(\cdot)$ function
ψ	10^{-13}	parameter from $v(\cdot)$ function
ε_z	0.002	size of the technology shock
ρ_z	0.99	persistence of the technology shock
ω_0	0.8	degree of interest rate smoothing
ω_1	0.5	coefficient of the response of R_t to $\widehat{\pi}_{t-1}$
ξ_w	0.75	fraction of households who do not change wages
ϕ	0.5	fraction of back-looking households (in Hybrid-Calvo)

Table 1: Calibrated parameter values
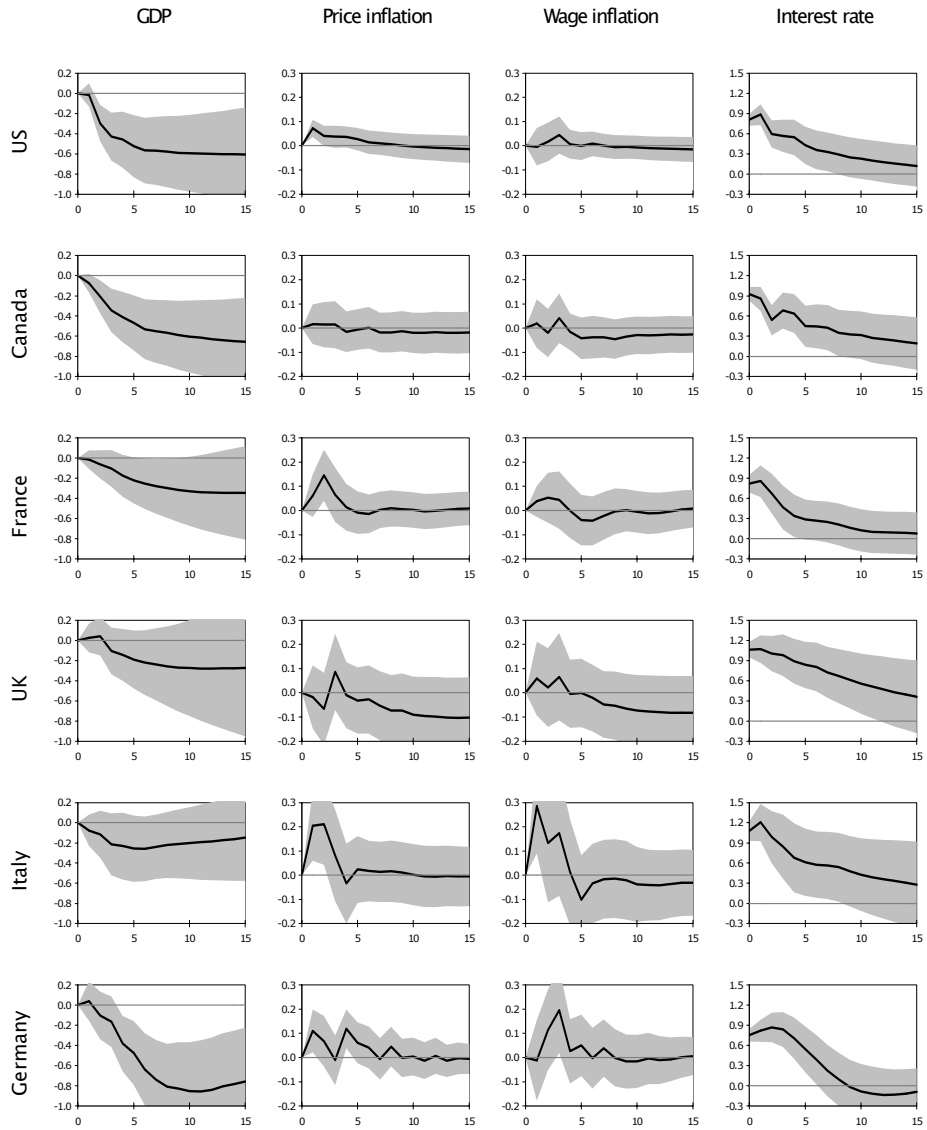
Figure 1: Response of several variables to a contractionary monetary policy shock.

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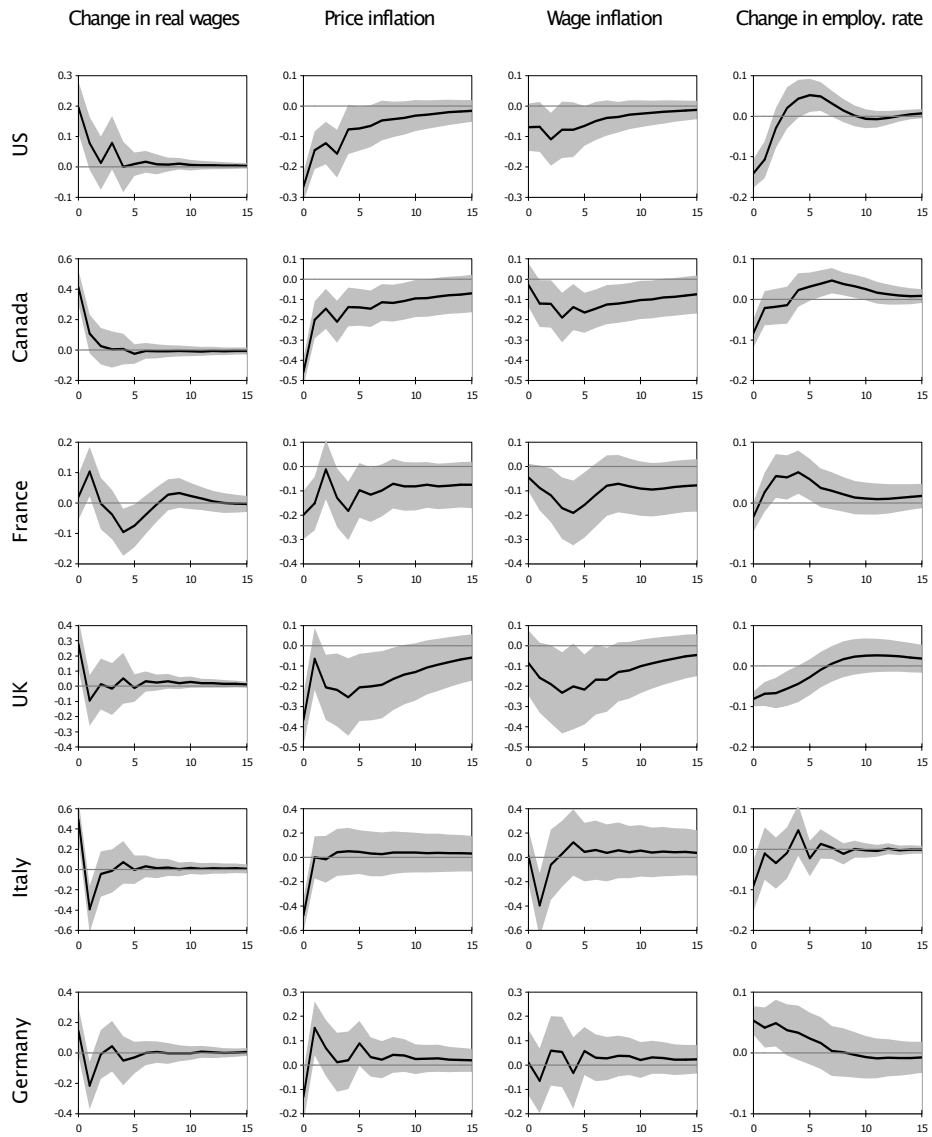
Figure 2: Response of several variables to a positive technology shock.

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Base Calvo model   Backward Calvo model   Hybrid Calvo model

Figure 3: Calvo models' responses to a positive technology shock.

Backward Calvo model   Sticky price model   Fair–wage model
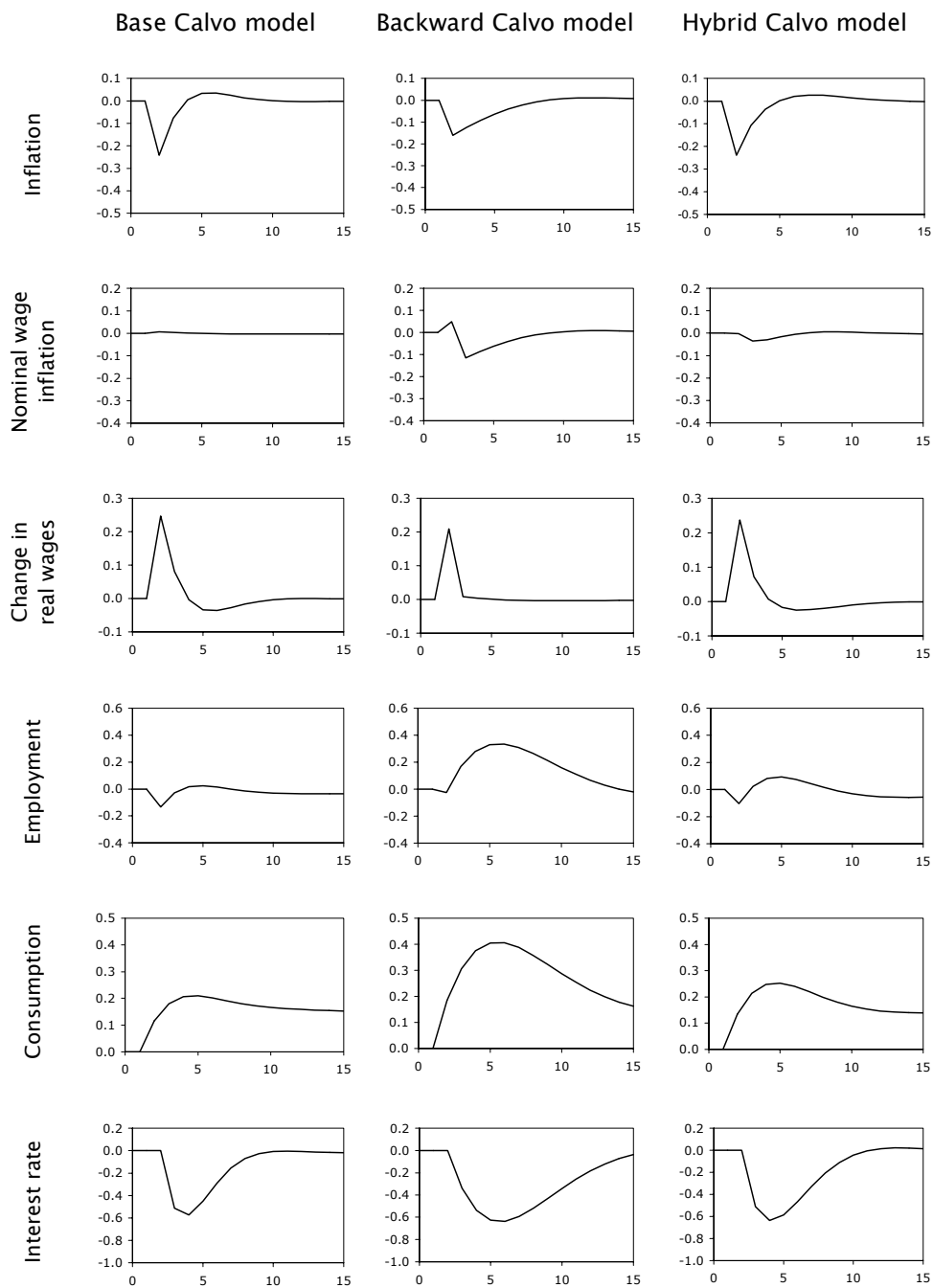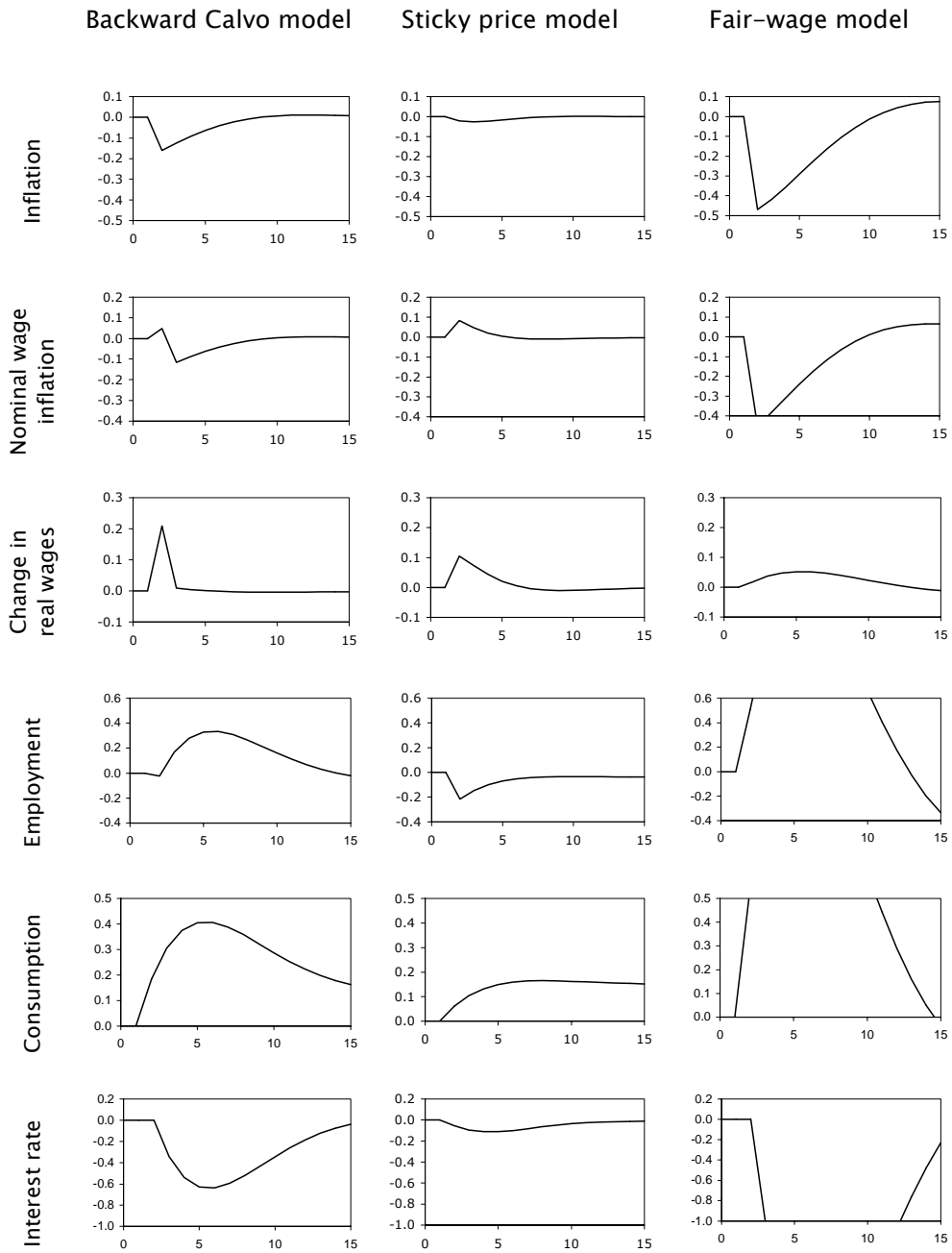
Legend:

Deviations from unshocked path (interest rates in annualised percentage points)

Figure 4: Comparison of responses to a positive technology shock across alternative models.
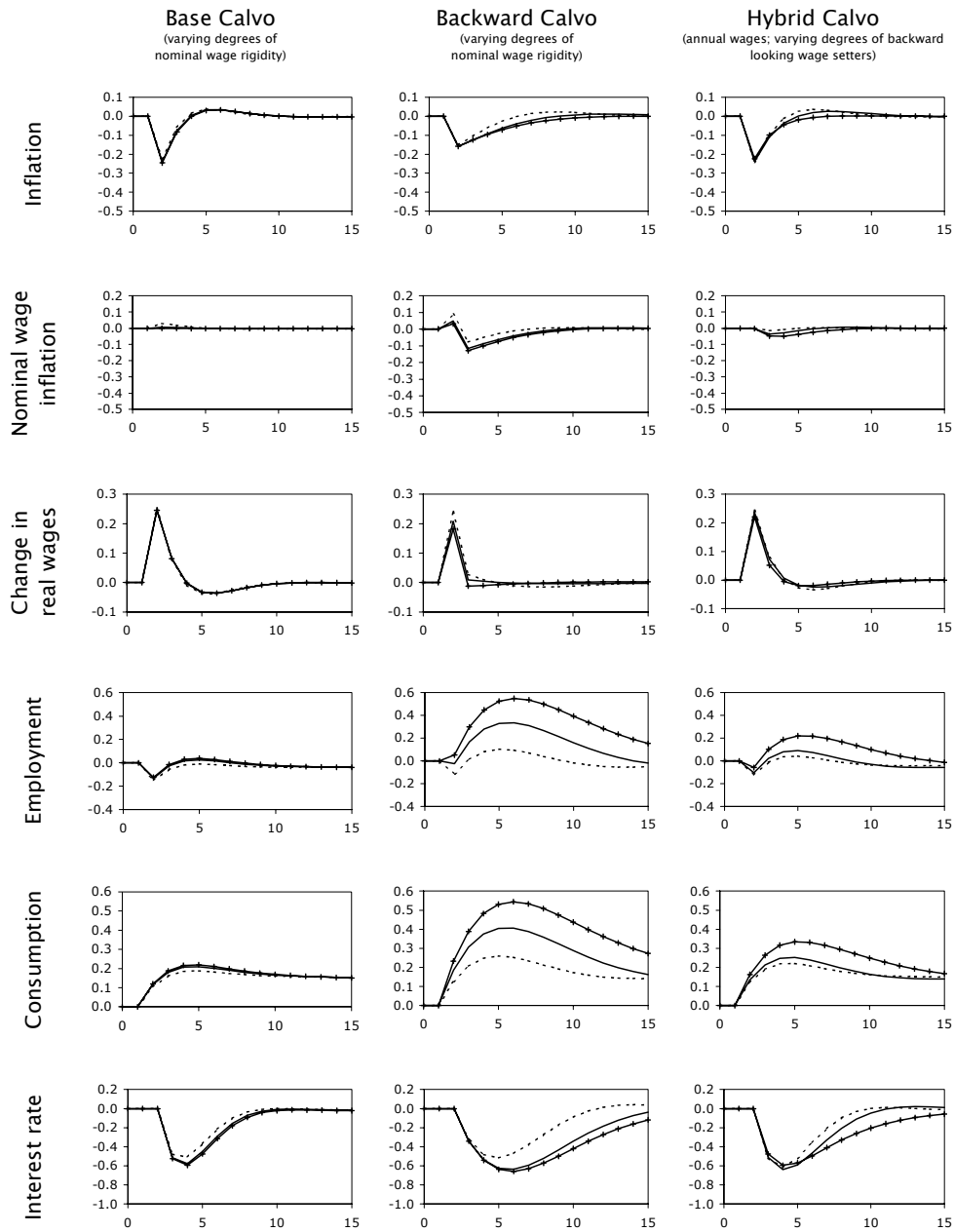
Legend:

Deviations from unshocked path (interest rates in annualised percentage points)

Base and backward Calvo models: Dashed: 2 quarters; Solid line: 4 quarters; Line with squares: 8 quarters
Hybrid Calvo models: Dashed: 25% backward–looking (b.l.); Solid line: 50% b.l.; Line with squares: 75% b.l.

Figure 5: Sensitivity analysis: varying the degree of wage frictions.

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Base Calvo
(varying interest rate rules)

Backward Calvo
(varying interest rate rules)

Hybrid Calvo
(varying interest rate rules)
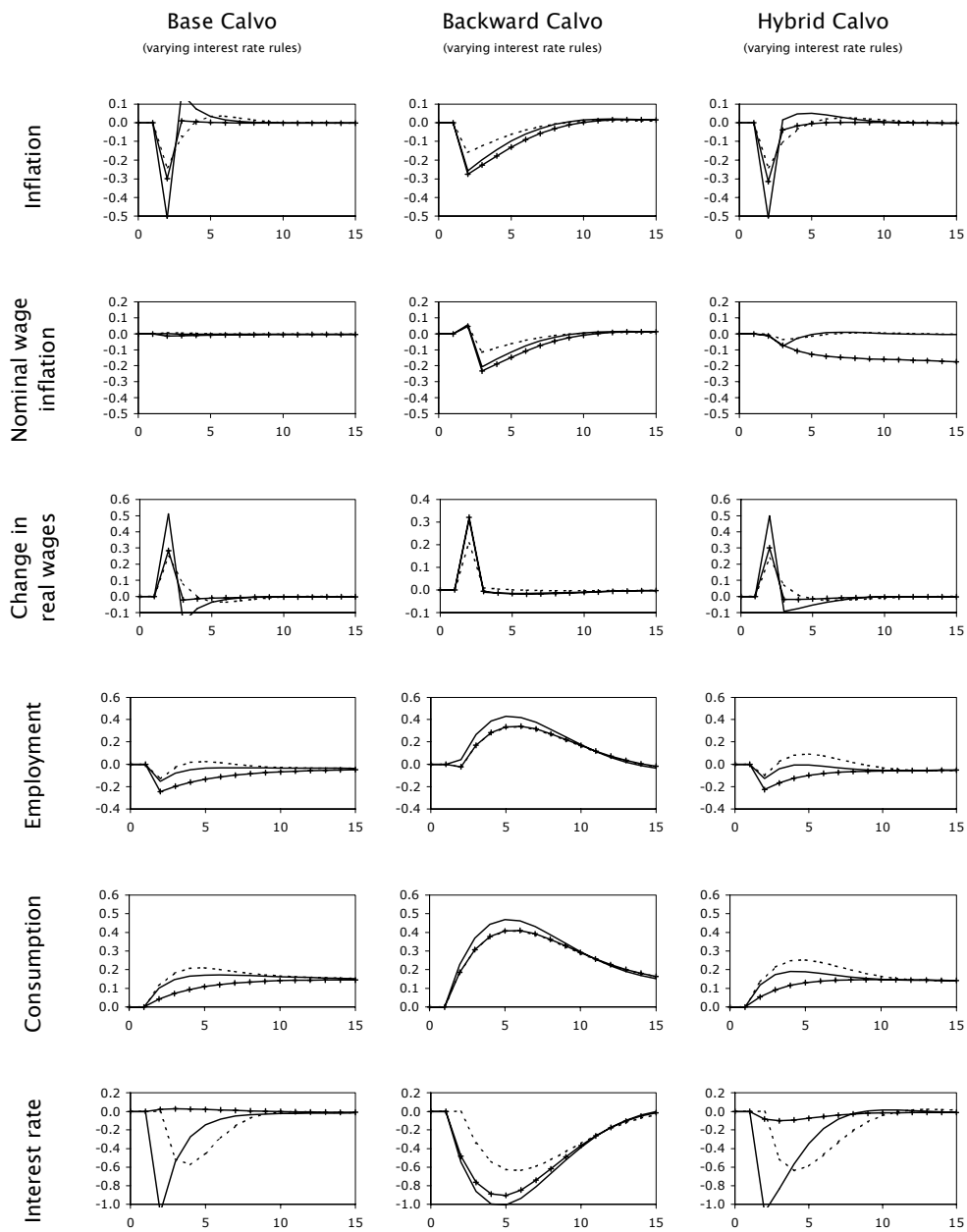
Legend:

Deviations from unshocked path (interest rates in annualised percentage points)

Dashed lines: backward rule; Solid Lines: contemporaneous rule; Line with squares: forward rule

Figure 6: Sensitivity analysis: varying the monetary policy rule.

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